A system that simultaneously measures the translational temperature, bulk velocity, and density in gases by collecting, referencing, and analyzing nanosecond time-scale Rayleigh scattered light from molecules is described. A narrow-band pulsed laser source is used to probe two largely separated measurement locations, one of which is used for reference. The elastically scattered photons containing information from both measurement locations are collected at the same time and analyzed spectrally using a planar Fabry-Perot interferometer. A practical means of referencing the measurement of velocity using the laser frequency, and the density and temperature using the information from the reference measurement location maintained at constant properties is provided.

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References Cited

U.S. PATENT DOCUMENTS


OTHER PUBLICATIONS


J.P. Drummond, et al.; “Development of Methods to Predict the Effects of Test Media in Ground-Based Propulsion Testing”; NASA Langley Research Center; Jan. 6, 2009; pp. 1-111; ANSI Std.


* cited by examiner
FIGURE 3 (a)
FIGURE 3(b)
SPATIALLY-AND TEMPORALLY-RESOLVED MULTIPARAMETER INTERFEROMETRIC RAYLEIGH SCATTERING SYSTEM AND METHOD

RELATED APPLICATIONS


STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under contracts NASW-99027, NNX07AC32A/2007 and NNX08AB31A/2008 awarded by NASA. The government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates to spatially and temporally resolved multi-parameter Interferometric Rayleigh scattering.

BACKGROUND OF THE INVENTION

Molecular-based diagnostics techniques capable of obtaining simultaneous multiple fluid properties such as temperature, density and velocity are critically important for characterizing the flows within airbreathing engines, such as scramjet engines and scramjet-turbine combined cycle engines for hypervelocity vehicles. At the other end of the velocity range, such techniques are needed to help in the development of the next generation of subsonic, low noise aircraft. Statistical correlations between these properties will lead to a more detailed understanding of the complex flow behavior as well as aid in the development of new turbulence models for scramjet engine flow path designs, and more accurate aircraft noise prediction tools. Required are instantaneous and simultaneous measurements of temperature, velocity, density, pressure, and chemical composition at multiple points in a gas when the spatial (hundreds of microns or less) and temporal (hundreds of nanoseconds or less) scales of the turbulent fluctuations are resolved. Specifically of interest are the mean properties and their turbulent variances and co-variances as well as the probability density functions. To date, diagnostics techniques to meet all these requirements on a single platform do not exist, but many linear and nonlinear optical techniques are available for partial achievement of this goal. One of these linear techniques, the Interferometric Rayleigh Scattering technique (IRS) (discussed in Bivolaru, D., Danehy, P. M., Gaffney, Jr. R. L., and Cutler, A. D., “Simultaneous Temperature and Velocity Measurements in a H2-air combustion flame (Hencken burner),” relative to simultaneous measurements in a reference N2-filled cell. The measurements are compared with the adiabatic flame theory predictions and the applicability of this method to turbulent flows is discussed.

In accordance with these and other objectives, a system is provided which simultaneously measures the translational temperature, bulk velocity, and density in gases by collecting, referencing, and analyzing nanosecond time-scale Rayleigh scattered light from molecules. A narrow-band pulsed laser source is used to probe two largely separated measurement locations, one of which is used for reference. The elastically scattered photons containing information from both measurement locations are collected at the same time and analyzed spectrally using a planar Fabry-Perot interferometer. A practical means of referencing the measurement of velocity using the laser frequency, and the density and temperature using the information from the reference measurement location maintained at constant properties is described. A simplified Gaussian distribution model to the scattered light spectra is used to obtain the flame properties. Corrections to this model are applied at lower gas temperatures when the simplified Gaussian approximation is no longer suitable. The near-zero measured velocity as a function of the measured flame temperature, and a comparison of the measured flame density and temperature with the perfect gas law are presented.

These and other objects of the invention, as well as many of the intended advantages thereof, will become more readily apparent when reference is made to the following description, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows the instrument configuration for simultaneous multi-point measurement of velocity, the gas translational temperature, and density at two largely-separated spatial locations. Legend: L-lens; M-planar mirror; BP-beam dump; PBS-polarization dependent beam splitter/combiner;
DP-Dove prism; F-P-Fabry-Perot interferometer; em-CCD-electron avalanche multiplication CCD camera; mv-measurement volume.

FIG. 2 shows Fabry-Perot interferograms containing multiple signals of elastically scattered light from two largely separated measurement locations, one of which is used for reference. The bottom horizontal pattern (exp1) is the signal obtained at the location of a H₂-air Hencken burner flame: (a), in air at 293 K outside the flame, and (b), in the flame at about 1560 K. The top horizontal pattern (exp2) is the signal from the secondary measurement location situated in a low-pressure N₂ gas cell at room temperature. This signal is used to reference the measurement of temperature and density performed at the flame location. The concentric ring pattern (ref1) is the spectra of unshifted laser light used to reference the Doppler frequency of all signals and facilitate computation of the gas bulk velocity at both locations.

FIG. 3 shows the combined Rayleigh and laser spectra obtained, (a), in atmospheric air at ~293 K, and (b), in H₂-air flame at ~0.5 (1637 K). The intensity scale is shown in arbitrary units (a.u.). Data contain ten instantaneous measurements to emphasize the trend (solid circles). Only one dataset (empty circles) is fit with a combined Gaussian-Lorentzian function (solid black line). The residual of the fit is shown with a line W.

FIG. 4 is a chart showing normalized spectral properties obtained simultaneously in H₂-air Hencken burner flame (~1.0, and ~0.5), and in the reference N₂-cell relative to atmospheric properties: (a), the spectral bandwidth, (b), the area of the spectra, and (c), the Doppler shift frequency. The inset on the top of the figure is a top view of the central section of the burner.

FIG. 5(a) is the measured gas density in air and in flame as a function of the measured temperature, compared with the perfect gas law (solid curve). FIG. 5(b) is the measured bulk velocity in air and in flame as a function of the measured temperature. The gas density and temperature are normalized with respect to the ambient air density (1.2 kg/m³) and temperature (293.5 K), respectively. The velocity is normalized by the maximum measurable velocity (3 km/s). Data obtained at atmospheric pressure during a full scan through a H₂-air Hencken burner flame at about ~0.5. The burner stabilization co-flow is nitrogen gas.

FIG. 6 is a combined single-shot interferogram of signal (horizontal pattern), frequency reference (concentric ring pattern), and density reference from an optical fiber (semicircular pattern).

FIG. 7 is an instantaneous image containing two interferograms of different spectral resolutions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In describing the preferred embodiments of the present invention illustrated in the drawings, specific terminology is resorted to for the sake of clarity. However, the present invention is not intended to be limited to the specific terms so selected, and it is to be understood that each specific term includes all technical equivalents that operate in a similar manner to accomplish a similar purpose.

The interferometric Rayleigh scattering (IRS) technique uses a narrow-band polarized laser source of wavelength λ₀ for probing gas molecules situated at a given measurement volume through photon scattering. Both elastic Rayleigh and inelastic Raman scattering of photons occurs. The inelastic scattering arises from changes in the rotational and vibrational states of the molecules during the scattering process. This process is weak and occurs in a different wavelength band than the laser wavelength. The Rayleigh scattering process is directly related to the spatio-temporal motion of the gas molecules and does not change the internal energy of the molecules. It is orders of magnitude stronger and occurs near the laser wavelength. The number of photons scattered are proportional to the incident laser energy. Receiving optics directly collect the scattered light (near λ₀) in a small solid angle, optically compare it with laser light for frequency reference, and analyze it spectrally with a high-resolution Fabry-Perot interferometer and a CCD camera detector.

The details of the spectral structure are related to the state of collisions between gas molecules traditionally divided in two regimes: hydrodynamic or collision dominated, and kinetic or collisionless regime (Rayleigh regime), without a clear border between them. The shape of the spectra is related to a non-dimensional ordering parameter γ = ω/κα, where ω = p/µ is the collision frequency (p is the gas pressure and µ is the shear viscosity) and κα is the acoustic spatial frequency (K is the magnitude of the resultant wave vector K and α is the speed of sound). For “s” type scattering, the angle between the electric field vector E of the incident light of wave vector k₀ (vertically polarized) and the direction of the scattered light of wave vector k₁ (horizontal direction) is β = 90°. The scattering angle θ is the angle between the direction of k₀ vector and the direction of k₁ vector along the optical axis of the receiving optics.

With these notations the resultant wave vector is \( \mathbf{K} = \mathbf{k}_0 - \mathbf{k}_1 \). Assuming that the wave vectors magnitudes are about the same \( |\mathbf{k}_0| = |\mathbf{k}_1| \), the magnitude of the resultant wave vector is \( K = 2k_0 \sin(\theta/2) \)

where \( k_0 = |\mathbf{k}_0| = 2\pi/\lambda_0 \). For very low density gases y is negligibly small and the Rayleigh spectra is approximated with a Gaussian shaped spectra. For moderate density gases, when collisions between molecules start to dominate (y~1), the spectra include a central peak (Rayleigh) and two Lorentzian-shaped sidebands (acoustic scattering or Brillouin). The Rayleigh contribution arrives from thermal fluctuations dissipating by thermal conduction. For large ordering parameters, the line width in frequency is given by \( D_\theta \mathbf{K}^2 \), where \( D_\theta \) is the thermal diffusivity. The Brillouin sidebands are symmetrically Doppler shifted about the central Rayleigh peak due to acoustic scattering from small pressure fluctuations in the gas (propagating at the speed of sound). They are located at \( \pm \mathbf{k} \alpha / 2 \mathbf{r} \), and their line width is given by \( F \mathbf{K}^2 \), where F is the sound attenuation coefficient. Then, the ratio of Rayleigh to Brillouin integrated intensities is \( (y-1) \), where y is the ratio of specific heats. This approximation fails in the kinetic regime when y is negligibly small.

At elevated temperatures for atmospheric pressure (or low pressures at room temperature) (y<<1), if we neglect the acoustic Brillouin scattering, the velocity distribution of molecules is Maxwellian. For one velocity component this is given by

\[
\frac{1}{\sqrt{2\pi m_\text{v}}} \exp(-\frac{(v-\bar{v})^2}{2m_\text{v}})
\]

where \( \bar{v} \) is the velocity of a molecule, \( v \) is the bulk velocity of molecules,

\[
\sqrt{(2k_0 Tm_\text{v})}\frac{1}{2}
\]

is the full width at 1/e height of distribution \( f(\xi) \), T is the gas temperature, \( k_0 \) is the Boltzmann constant, and m is the molecular mass. The bulk velocity \( v \) is what is observed at macroscopic scale. For a gas at rest the bulk velocity is zero and the average molecular random velocity \( v = \sqrt{\langle v^2 \rangle} \) due to deviations of \( \xi \) from \( v \) is also zero.
Photons of frequency $v$ from the incident probing beam are scattered from molecules moving in all directions with the random velocity $u$, and are shifted in frequency according to the Doppler effect

$$df(v) = (v - v_0) / c (u / v)^2,$$  \hspace{1cm} (4)

Therefore, for a component of velocity along the resultant wave vector $K$ one can relate the velocity distribution of the molecules to the scattered light frequency by rewriting Eq. (2) as

$$f(v) = (v - v_0)^{-2} \exp(- (df(v)^2),$$  \hspace{1cm} (5)

where the new spectral width in frequency is

$$\sigma(v) = (2K_u / m)^{1/2} \sin(\theta / 2) \lambda_0,$$  \hspace{1cm} (6)

In a gas mixture (as for example in air or in a flame) the spectral distribution of the scattered light is a sum of distribution with contributions from each molecular species weighted by their molar fraction $x_\gamma$, and the differential scattering cross-section $\sigma_\gamma$. Therefore one can write

$$I(v, v_\gamma) = \int f(v) \sigma_\gamma d\gamma,$$  \hspace{1cm} (7)

where $I_\gamma$ is the laser intensity, and $N$ is the total gas number density. The constant of proportionality $C$ depends on the laser polarization, and wavelength; the size of the probe volume; and the solid angle of the light collection optics (collecting power), the collection direction, and the detector quantum efficiency.

To determine the gas properties, the scattered light spectra and the laser spectra are analyzed with theoretical models by least-square fitting techniques using the laser spectra as reference for Doppler shift calculations. Research efforts to extract the properties of gases by analyzing the spectra of scattered light with Fabry-Perot interferometers include in diluted gases, in low-speed combustion flames, and in high-speed rocket external flows. The use of kinetic models to obtain spectral information requires prior knowledge of gas parameters (that are not measured by the instrument) such as the internal specific heat per molecule, the ratio of shear to bulk viscosity, and the ratio of shear viscosity to thermal conductivity. This model is difficult to use since these parameters are not precisely known and there is limited data available for the species and range of temperatures required for measurements. In this work a simplified Gaussian-Lorentzian analytical model is used, easy to apply to the data, instead of a more detailed computational Rayleigh-Brillouin kinetic model. Then, corrections of these measured quantities via calibrations are applied to obtain quantitative information within an acceptable margin of error as it will be shown later.

FIG. 1 is a non-limiting embodiment of the instrument design in accordance with a preferred embodiment of the invention. The system 100 references all measurable properties, the velocity, the temperature, and the gas density. This is performed with an optical setup that simultaneously records the spectral properties of Rayleigh scattered light from two largely separated measurement locations, one of which is used for reference. To increase the incident laser energy probing the measurement volume, and implicitly to increase the scattered signal, this system uses for probing two collinear laser beams slightly delayed in time for probing the gas sample. The laser source is a seeded dual Nd:YAG laser, with a wavelength $\lambda_0$, of 532 nm, variable timing between pulses, 10 Hz repetition rate, nine nanoseconds pulse width and 0.005 cm$^{-1}$ bandwidth.

As shown, the probing laser beam (of wave vector $k_\gamma$) 102 is focused at the measurement volume (mvl) 106 by the $L_1$ lens 104 and collected and re-collimated for further use by the $L_2$ lens 108. The $L_7$ lens refocuses the recovered laser beam after passing through mvl to generate the second measurement volume mvl2. Thereafter, the remaining beam energy is lost in the beam dump BD. The elastically scattered light pulse (exp1) (of wave vector $k_\gamma$) 120 is collected and collimated from the measurement volume mvl1 106 by the $L_3$ lens 112 (which can have an f/4, 250-mm focal length, and is located 250 mm from the measurement volume mvl1 106). The beam diameter of this signal is reduced to match the analyzing optics aperture diameter (~15 mm) using the beam reducer/expander formed by lenses $L_{14}$ and $L_{16}$, and directed using the mirror $M_{118}$ toward the polarization dependent beam combiner PBS 122. The beam combiner PBS 122 facilitates the optical path of the signal with the un-scattered light (refl) 124 used for frequency referencing.

In the present configuration, the polarization dependent beam combiner PBS 122 is used to also combine this beam (exp1) 120 with a second beam (exp2) 130 collected by the $L_4$ lens 136 from a secondary measurement volume mvl2 140. This measurement volume 140 is located in a gas cell with known gas properties that is used for properties referencing as will be shown later. Similarly, this beam (exp2) 130 is reduced and collimated by the lenses $L_{14}$ 134 and $L_{16}$ 132, and directed by mirror $M_{126}$ toward the combiner PBS 122. The light polarization of both signals is adjusted (not shown) such that the PBS 122 reflects the second beam exp2 130 together with the transmitted main beam 120 toward the Fabry-Perot interferometer (F-Pi) 142. The reference laser light 124 needed for frequency referencing is optically mixed with the signals at the PBS 122 by passing un-shifted laser light through the mirror $M_{126}$ (or any other mirror, such as mirror $M_{118}$). Therefore the interferogram formed by the F-Pi interferometer 142 and imaged by the $L_{4}$ lens 144 on the CCD camera 146 contains the spectra of exp1 120, exp2 130, and refl 124.

FIG. 2 shows examples of interferograms containing multiple Rayleigh signals (exp1 and exp2) obtained in the cell (top horizontal pattern) and at the flame location (bottom horizontal pattern), in room air (293 K in FIG. 2(a)) before flame ignition, and in an H2-air flame at equivalence ratio $\phi = 0.5$ (1560 K in FIG. 2(b)), respectively. The circular pattern is the interferogram of the laser light used for frequency referencing (ref1). To avoid the eventual overlap of the closely spaced spectra exp1 and exp2 the pattern of exp2 could also be rotated in the image plane (for example by 90° or any other angle) using the Dove prism DP 128.

As mentioned earlier, in this arrangement the energy deposited at the measurement volume is increased by spatially overlapping the two collinear laser beams slightly delayed in time. Additionally optical aberrations are introduced in the optical path of the focusing lens through lens tilting. This beam shaping is achieved by tilting the focusing lens $L_1$, slightly, $5^\circ$ to $22^\circ$ depending on the laser energy, and thereby introducing an astigmatism aberration of the beams at their foci. The tilting is performed about an axis perpendicular to the plane containing the incident laser beam and the signal collection direction. The elliptical beam allows more energy to be deposited in the flow without gas breakdown. This results in larger Rayleigh signal intensity if collected from a direction in the plane of the beam and the major axis of the ellipse, at the cost of reduced spatial resolution in the other dimension. In the experiments reported here a total of 385 mJ in two laser pulses separated in time by about 200 nanoseconds and a ratio of major to minor axis of the elliptical beam.
of about 10 at its first focus were used. The measurement volume is about 0.05 mm\(^3\) to 0.2 mm\(^3\) to 0.5 mm. Both L\(_2\) and L\(_3\) lenses collect scattered light from the measurement locations at an angle \(\theta\approx90^\circ\) with respect to the corresponding probing laser beam direction. The Fabry-Perot interferometer is made of solid glass with a free spectral range (FSR) of 8 GHz and a finesse of about 22. This defines the maximum measurable Doppler shift and therefore the dynamic range for measuring velocities to about \(\pm1.5\) km/s when no prior velocity direction is known, or to about 3 km/s if the velocity direction is known. The range of measurable temperatures and densities in gases is from cryogenic temperatures to about 2500 K (limited at high temperatures by the overlap of consecutive orders of interference), and from 0.1 kg/m\(^3\) to about 2 kg/m\(^3\) (limited by the CCD dynamic range), respectively. The working medium of the invention is situated in a non-premixed near-adiabatic H\(_2\)-air Hencken burner flame at atmospheric pressure (also used to calibrate the CARS measurements). The burner is placed vertically at the first measurement volume (mv1) in a direction perpendicular to the scattering plane. The hydrogen fuel and the air oxidizer are assumed to mix immediately above the burner surface. The burner surface is a 25.4 mm \times 25.4 mm rectangular section of hypodermic needle tubes for fuel and honeycomb passages for oxidant surrounding by a rectangular region of co-flow honeycomb design (a total of 36.5 mm\(^3\)) to 36.5 mm square surface). The H\(_2\) and air equivalence ratio \(\phi\) is varied from 0.1 to 1, by varying the flow rates (up to 0.5 l/sec). A constant flow of N\(_2\) of 0.4 l/sec was directed through the co-flow nozzle at all fuel-air mixtures to improve flame stability and provide an almost dust-free environment for the instrument. The molecular content in the co-flow-flame interface is considered unknown. The flame temperature and species molar fractions in the flame region were calculated from the adiabatic flame theory.

The primary species are N\(_2\), O\(_2\), H\(_2\)O, and H\(_2\), with the minor species (Ar, CO, OH, etc.) being neglected. The main product of combustion is water (H\(_2\)O) in the gaseous state with negligible contribution from condensate. The perfect-gas law for the mixture is \(p/(\text{R/m})/T\), where m is the molecular weight of the mixture (kg/kmole), p is the gas pressure (N/m\(^2\)), \(\rho\) is the density (kg/m\(^3\)), and T is the gas temperature (K), and the perfect-gas constant R = 8314.5 J/(kmole)(K). The experiments are performed in room air (\(\text{m}_{\text{air}}\approx28.97\) kg/kmole) at the atmospheric pressure \(p_{\text{air}}\) (101324.72 N/m\(^2\)), temperature \(T_{\text{air}}\) (293.5 K), and density \(\rho_{\text{air}}\) (1.2 kg/m\(^3\)). The axial velocity of the flow (vertical direction) non-influenced from flow rates at room temperature to about 10 m/sec, but higher velocities of this order of magnitude are expected during combustion. The radial velocity component (horizontal direction, measured in this experiment) is considered to be much smaller than the axial velocity (near zero).

The second measurement volume is situated in a constant properties glass cell containing N\(_2\) at room temperature (293.5 K). The glass cell is connected with manual valves and plastic tubing to a feedstock of N\(_2\) gas and to a vacuum pump. The initial air in the cell is removed with the vacuum pump and the N\(_2\) is let in to the desired pressure before measurements. A pressure of \(p_{\text{N}_2}=25.6\) kPa (198.5 torr) was used for the reported experiments. Lower pressure was used to ensure that the density and the y-parameter are similar to those in the combustion flow, which made the signals from both channels comparable.

Verification of the instrument is performed by obtaining all scattered light spectral properties simultaneously in the atmospheric flame and nitrogen (N\(_2\)) cell. Single-shot spectra 1(v) obtained in the air and H\(_2\)-air flame are shown in FIG. 3. The data are shown with solid and empty circles. The best fit to the data shown with empty circles using the sum of a Gaussian function for the scattered spectra and a Lorentzian function for the reference laser spectra is shown with a continuous line. Ten single-shot spectra are overlapped to the fitted data (solid circles) to emphasize the trend.

FIG. 3(a), and FIG. 3(b), show the spectra obtained in atmospheric air at the conditions described earlier, and in the flame at \(\phi=0.5\) (~1637 K), respectively. The energy of the laser was maintained approximately constant during these measurements though any variations in laser intensity would be corrected by the data obtained in the reference cell. The parameter y for air at atmospheric conditions is 0.8 so the maximum error of the measurement obtained by estimating the molecular weight is about 16% in the small range of molecular weights are possible. For example, in the calculation of \(T_{\text{m}}\), from the spectra shown in FIG. 3, the broadest Rayleigh spectra shown in FIG. 3(b) cannot be attributed to cold gases (higher molecular weights) that will produce the spectra shown in FIG. 3(a). The maximum error possible in these computations without considering this approximation of the molecular weight is about 16% in the whole range of measurable temperatures presented here. The actual error of the measurement obtained by estimating molecular weights as explained in this approximation is considered to be only a fraction of this maximum error.
To obtain the bulk velocity of the gas, the spectra are analyzed for the average spectral shift frequency relative to the laser spectra. From Eq. 4, if all molecules move with the bulk velocity v, the spectra is Doppler shifted from the laser frequency v_0 by \((v-v_0)\cdot v_0 = 2(\cos\theta_1 - v_0)\), where \(\cos\theta_0\) is the frequency reference of the laser.

In a usual configuration for measuring gas density, to keep the measurement unaffected by the fluctuation in laser energy from shot to shot, a reference measurement of the laser energy is implemented by recording a part of the signal or the laser intensity. The solution for a reference adopted in this work is a secondary measurement volume located in a glass cell containing a gas with known pressure, temperature, and composition. By normalization with the cell total intensity \(A_0\), the laser energy fluctuations from pulse to pulse during the measurement are minimized. Additionally, the measured cell parameters provide simultaneously a reference for the known gas density, temperature, and velocity (zero for stagnant gas).

Integrating over the solid angle of the collecting optics and rewriting in dimensionless quantities, Eq. (7) becomes:

\[
p_m = C_2 A_0 v_0 \left(1 - \frac{v_0}{c} \sin\theta_1\right) \left(1 - \frac{v_0}{c} \sin\theta_2\right)
\]

The measured signal can be computed by integrating the spectral shift frequency relative to the known quantities in the cell (N_2) and in air at the measurement volume.

The velocity is normalized by the maximum measurable frequency (defined by the interferometer) shown in FIG. 4(a) in a plane situated at about 38.5 mm above the burner surface (similar measurements of rotational-vibrational temperature using CARS were performed by Hancock (“Nitrogen and Hydrogen CARS Temperature Measurements in a Hydrogen/Air Flame Using a Near-Adiabatic Flat-Flame Burner,” Combustion and Flame, Vol. 109, No. 3, 1997, pp. 323-331)). The Doppler shift frequency obtained in flame at equivalence ratio of \(\phi = 1.0\) (line X) and \(\phi = 0.5\) (line Y), relative to the known quantities in the cell (Z trace). Data is extracted from single-shot interferograms using Gaussian and Lorentzian fit functions as approximation for the Rayleigh and laser spectra. FIG. 4(a) shows the normalized spectral bandwidth \(W_m\) measured at the flame location. The normalized factor is the spectral width \(W_m\) obtained at this location in air at room temperature (-293.5 K). The width obtained in the N_2 cell, about 9% narrower than the width in the air, can also be used for reference. FIG. 4(b) shows the integral of the signal intensity measured at the flame location, relative to the integral of the signal obtained in the cell, corrected for the cell signal intensity relative to the flame signal intensity. The core flame cross section, where the flame properties are almost uniform, is about 20 mm x 20 mm. The measurement volume was scanned along a line from one side to the other over the center of the burner (shown in the inset image of FIG. 4) in a plane situated at about 27 m/s in the flame core (and increases to 39 m/s at \(\phi = 1\)). It should be noted that this instrument was not intended to measure near-zero velocities, but rather supersonic/hypersonic ones (up to 3 km/s). Therefore the error of measuring near zero velocity is less than 1% of the dynamic range of the interferometer free spectral range.

As shown in FIG. 5(a), the measured gas density dependence on the measured translational temperature (blue symbols), agrees very well with the perfect gas law (solid curve) computed for this case. In this computation the gas temperature and composition is assumed to be only a function of \(\phi\) so the gas molecular weight can be inferred as a function of the temperature outside of the flame core where \(\phi = 0\) is unknown. The measured velocity dependence on the flame temperature is shown in FIG. 5(b). The rms (root mean square) variations that include true instantaneous errors and spatial and temporal fluctuations of the flow. As expected, the mean velocity is near zero, and the rms fluctuations (zone standard deviation) of velocity increases with increasing temperature from about 11 m/s at the room temperature (and in the cell) to about 27 m/s in the flame core (and increases to 39 m/s at \(\phi = 1\)). It should be noted that this instrument was not intended to measure near-zero velocities, but rather supersonic/hypersonic ones (up to 3 km/s). Therefore the error of measuring near zero velocity is less than 1% of the dynamic range of the interferometer free spectral range. A backward scattering direction (more sensitive to Doppler shift) could be selected.

To our knowledge, these high resolution temporal and spatial measurements of simultaneous gas translational temperature, velocity, and density using interferometric Rayleigh scattering are the first to be performed in H2-air combustion flames.

Thus, the invention provides a non-intrusive optical diagnostic technique for temporally and spatially resolved measurements of multiple properties in reacting and non-reacting gases. The system employs a narrow-band pulsed laser source.
at 532 nm for simultaneous probing of molecules through
elastic light scattering at two largely separated measurement
locations, one of which is used for reference. The collected
photons containing information from both measurement
locations are analyzed spectrally with a planar Fabry-Perot
interferomet. The reference measurement is located in a
cell containing N₂ gas at low pressure (26.5 kPa) and
room temperature (293.5 K). The measured cell spatial
properties on a reference for known gas
temperature, translational temperature (the
spectral width), and supplementary near-zero gas velocity
(zero average Doppler shift). Additionally, the cell spatial
intensity provides the normalization factor for the laser
energy fluctuations critical for the measurement of density.
These spectral properties are used to calculate, by normaliza-
tion, the gas density and translational temperature at the me-
asurement location. The range of measurable temperatures and
densities in gases is from cryogenic temperatures to about
2500 K (limited by the interferometer), and from 0.1 kg/m³
to
2 kg/m³ (limited by the CCD dynamic range), respec-
tively. The maximum dynamic range for measuring velocities
is about ±1.5 km/s when no prior velocity direction is known,
or about 3 km/s if the velocity direction is predictable.

In a laboratory demonstration, the measurement location is
situated in a non-premixed near-adiabatic H₂-air Hencken
burner flame at atmospheric pressure. The referenced mea-
surements at different flame conditions compare favorably
with the flame temperature and the gas density (up to the stoichiometric flame temperature of 2377 K) computed with
the adiabatic flame theory. The random errors of measuring
the flame properties, the translational temperature, velocity,
and the gas density at the maximum measurable gas temper-
aturate, are estimated to less than about 17%, 39 m/s and 5%,
respectively. These errors include the spatial and temporal
variation of these properties across the flame.

The invention demonstrates simultaneous referencing
(calibration) while performing measurements of velocity,
density, and temperature with the interferometric Rayleigh
scattering technique described here. In particular, the inven-
tion can be used for simultaneous multi-property turbulence
studies of subsonic, supersonic, and hypersonic, nonreacting
flows and predictable composition reacting flows in the range
of temperatures, turbulence levels, and errors described above.

In another embodiment of the invention, an optical setup is
implemented in which only one Rayleigh scattered light pulse
(signal exp1) is collected from the measurement volume
(mv1) by the L1 lens, and collimated and directed toward the
PBS. Referring to FIG. 1, the PBS is used to inject the beam
into a recycling optical path formed by the input mirror of the
first interferometer F-Pi situated on the first optical axis and
the input mirror of a second interferometer (E2) - not shown
situated on a second optical axis perpendicular to the first
optical axis. This interferometer replaces mirror M₁, and is
adjusted such to reflect the signal received from PBS. A
quarter-wave plate (QWP—not shown) located between the
PBS and F-Pi rotates the polarization of the input beam exp1
to circular polarization.

The signal pulse polarization from mv1 is adjusted such
that the PBS sends it toward the QWP and interferometer F-Pi
first, and reflects it towards the QWP, PBS and the second
interferometer (E2) afterwards. A small fraction of this light
is transmitted through either interferometer, but most of it
(depending on interferometer reflectivity) is reflected back
into the opposite interferometer. In the usual arrangement, not
containing the second interferometer this rejected light from
F-Pi is lost. In the disclosed optical arrangement the reflected
light by the F-Pi input mirror is reflected back on the optical
axis again by the interferometer input mirror of the second
interferometer. At the second reflection the QWP rotates the
polarization to the initial input polarization and the remaining
beam energy is lost on the first optical axis. This is demon-
strated in Bivolaru, et al., “Multipoint Interferometric Ray-
leigh Scattering using Light Recirculation,” AIAA-2008-
23-26, 2008, using a mirror instead of a second interferometer
(see also Bivolaru et al., U.S. Pat. No. 7,414,708). Optical
means (not shown) directs the light passing through E2
toward L6 to generate a second interferogram.

In a further aspect, the interferometer F-Pi is selected for
the maximum range of measurable velocities while the sec-
tion of a much lower range (or vice versa), e.g., with the
free spectral range of 8 GHz (low spectral resolution) and
3.75 GHz (high spectral resolution), respectively. The inter-
ferometer F-Pi is used to remove the ambiguity in the sign
of the velocity being measured, while the second one measure it
accurately. At higher temperatures this interferometer cannot
be used due to a overlap of the consecutive interference
orders, the second interferometer suffices. Similarly, at very
low gas temperatures (<290 K) when the Rayleigh spectra are
narrow, the second interferometer suffices. The dynamic
range and accuracy of the instrument can be adjusted by
selecting the free spectral ranges of the interferometers,
depending on the application.

In a further aspect, for the disclosed implementation a
second direct-viewing collecting optic (similar to lenses L1,
L2 and L3) collects and collimates Rayleigh light (ref2) from
a second measuring volume situated in a controlled environ-
ment, FIG. 1. The light polarization is adjusted and directed
such that the PBS reflects it toward F-Pi. After one pass
through the interferometer the reflected signal cannot be
recovered and is lost. To avoid the overlap of spectra, the
reference pattern of ref2 is rotated 90° in the image plane
using the Dove prism DP. Therefore the interferograms gen-
erated by both interferometers, contain the spectra of exph1,
ref1 (probing laser spectra), and ref2 (reference spectra), and
the spectra of exp2 (the high resolution Rayleigh spectra) and
ref1, respectively.

In another embodiment of the invention, a single direct-
viewing optic is used to collect light from two (or more)
largely-separated measurement volumes. One (or more)
mirror(s) or equivalent optics placed in close proximity to the
lens L1 location, receives and transmits (toward the lens) light
from additional measurement volumes. One measurement
volume is used for direct probing as in the new or prior art
while the secondary measurement volumes are used for mea-
surements of density, temperature, and velocity in conjunc-
tion with one or more reference cells, or known gas flows.
An example of a density (velocity and temperature) reference
cell layout is shown in FIG 1; or an imaging optical fiber(s) that
collect signal(s) from widely separated measurement or refer-
ce location(s). An example of an interferogram used to
combine two signals, one directly from a measurement vol-
ume (vertical pattern), and one from an imaged optical fiber
used for density reference (three semi-circular sectors) is
shown in FIG. 6. The optical fiber collects light remotely from
a density reference cell. The circular pattern is the interfer-
ogram of the laser light used for frequency reference.
FIG. 6 is for a combined single-shot interferogram of sig-
nal, frequency reference, and density reference from an optical
fiber. The single shot image shows an interferogram of a
signal collected from the measurement volume, an interfer-
ogram of signal from a secondary measurement volume used
as density reference, and an interferogram of the probing laser
light used as a frequency reference. Thus, a single-shot inter-
ferogram is provided which combines a signal from a direct view optic as described previously, a frequency reference, and a density reference from an optical fiber.

In another embodiment of the invention shown in FIG. 7, the output fringe pattern of both interferometers are optically combined in a single beam and imaged onto a single high-sensitivity CCD camera. FIG. 7 shows the instantaneous image containing two interferograms of different spectral resolutions. A first interferogram 220 is shown having a free spectral range (FSR) of 3.75 GHz (F-Pi). A second interferogram 224 is shown having an FSR of 8 GHz (E2). The horizontal pattern 222 shows the additional non-spectrally resolved density signal delivered parallel with expl from the measurement volume. The vertical pattern 228 shows the spectrally resolved signal from the cell for referencing the density measurement (rec2). The frequency reference patterns (ref1) 226 are also shown. This provides better accuracy at lower velocities while preserving a large dynamic range. And, eliminates the Doppler shift sign ambiguity at higher velocities.

In another embodiment of the invention, the signal is further increased by increasing the laser energy deposited at the measurement volume without inducing the gas breakdown. A laser sheet or an elliptical beam at its focus allow more energy to be deposited in the flow, resulting in larger Rayleigh signal intensity if viewed from a parallel direction and more accurate measurements, at the cost of reduced spatial resolution in the other dimension. This can be achieved by tilting the focusing lens L, slightly (5-30 degrees) thereby introducing astigmatism, by using a combination of cylindrical and spherical lenses, or by a pair of anamorphic prisms or similar to generate a laser sheet.

In another embodiment of the invention a laser sheet generated by tilted lens L, is viewed from a perpendicular direction such to permit two-dimensional measurements of parameters without decreasing the equivalent signal obtained from a single circular cross-section beam.


The description and drawings of the present invention provided in the paper should be considered as illustrative only of the principles of the invention. The invention may be configured in a variety of size, shapes, and optical elements, and is not intended to be limited by the preferred embodiment. Numerous applications of the invention will readily occur to those skilled in the art. Therefore, it is not desired to limit the invention to the specific examples disclosed or the exact construction and operation shown and described. Rather, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

The invention claimed is:

1. A system for analyzing properties of gaseous media, comprising:
   - a laser source providing a narrow-band pulsed laser which probes a location in the gaseous media and a reference location;
   - a first optical element collecting scattered light from the gaseous media;
   - a second optical element collecting scattered reference light from the location reference light and scattered reference light by said second optical element.
   - a polarization dependent beam combiner
   - first Fabry-Perot interferometer receiving the mixed light signals from said beam combiner.
2. The system of claim 1, further comprising an interferometer receiving the mixed laser from said beam combiner.
3. The system of claim 2, further comprising a CCD camera for imaging the light from said interferometer.
4. The system of claim 3, further comprising a processor for analyzing the light from said interferometer to identify properties of the gaseous media.
5. The system of claim 4, wherein the system operates in real time to provide a diagnostic of gaseous media flows.
6. The system of claim 1, wherein the system operates in a range of temperatures, velocities, and gaseous media densities.
7. The system of claim 1, wherein the gaseous media is in the form of clusters of molecules (Mie scattering).
8. A system for spatially and temporally resolving multiple parameters of a gaseous media sample, the system comprising:
   - a probing laser source providing a narrow-band pulsed laser source;
   - a first optical element for focusing the laser on the gaseous sample;
   - a second optical element collecting and collimating scattered light from a gaseous sample;
   - a first beam reducer/expander reducing a diameter of the collected and collimated scattered light from the gaseous sample;
  - polarization dependent beam combiner;
   - a first mirror directing the scattered light from said beam reducer/expander to said beam combiner;
   - a third optical element collecting and re-collimating the laser passing through the gaseous sample;
   - a second mirror directing the laser from said third optical element;
   - a fourth optical element focusing the recovered and collimated laser on a reference measurement volume with known gaseous media properties;
   - a second beam reducer/expander reducing the diameter of the scattered light received from the second optical element;
   - a third mirror directing the scattered reference light from said second beam reducer/expander to said beam combiner, whereby said beam combiner optically mixes the scattered light from said first mirror with an unscattered light used for frequency referencing, and with the scattered reference light from said third mirror; and,
   - a first Fabry-Perot interferometer receiving the mixed light signals from said beam combiner.
9. The system of claim 8, wherein the unscattered reference light passes through said third mirror toward said beam combiner.
10. The system of claim 8, wherein said first, second, third, and fourth optical elements each comprise a lens or a combination of lenses.
11. The system of claim 8, wherein said first and second beam reducer/expanders each comprise two lenses.
12. The system of claim 8, wherein the said system probes one location in a gaseous media using simultaneously two interferometers in a signal recycling configuration, the signal recycling configuration comprising:
   - a quarter-wave plate located between the beam combiner and the first Fabry-Perot interferometer, wherein the said quarter-wave plate modifies linear polarization of an incoming light beam to circular polarization.